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ASSESSMENT OF THE TECHNICAL CONDITION OF ASYNCHRONOUS TRACTION MOTORS OF MAINLINE ELECTRIC LOCOMOTIVES

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Abstract: This paper investigates the factors affecting the operating conditions of asynchronous traction motors in mainline electric locomotives under the climatic conditions characteristic of the mountainous regions of Uzbekistan. The influence of adverse environmental conditions on the thermal state, reliability, and service life of traction motors is analyzed. Particular attention is paid to the importance of thermal condition monitoring and prediction for improving the operational reliability and efficiency of electric locomotives.

Keywords: asynchronous traction motor; mainline electric locomotive; thermal condition; climatic conditions; mountainous regions; motor reliability; temperature prediction; technical diagnostics.

Introduction

At present, railway transport is one of the key strategic sectors of Uzbekistan's economy. The continuous growth in freight and passenger transportation between different regions of the country requires railway transport to operate with a high level of reliability and continuity. In particular, mainline electric locomotives operating in mountainous areas with complex terrain are subjected to severe operating conditions and increased mechanical and thermal loads. Under such conditions, the technical condition and thermal regime of asynchronous traction motors, which constitute the primary traction units of electric locomotives, become critically important.

Asynchronous traction motors are the principal electromechanical energy conversion devices responsible for generating the locomotive's tractive effort. Their reliable operation directly determines the operational efficiency, safety, and serviceability of the entire locomotive. During operation, high traction loads, prolonged low-speed operating modes, and unfavorable climatic conditions significantly affect the thermal behavior of the traction motors. Excessive temperature rise accelerates the aging of winding insulation, increases bearing wear, and contributes to the occurrence of various technical failures. Therefore, evaluating the technical and thermal condition of asynchronous traction motors, as well as monitoring and predicting their temperature characteristics, represents one of the most important scientific and engineering challenges in modern railway transportation. [4,5]

Modern mainline electric and diesel locomotives are widely employed in Uzbekistan's railway network for both freight and passenger transportation. Among the principal traction rolling stock are the **"O‘zbekiston"**, **OZ-EL**, **OZ-ELR**, **3ES5K**, **2OZ-UY**, and **2OZ-ELR** electric locomotives, as well as the **UzTE16** and **TEP70** diesel locomotives [6]. Contemporary electric locomotives are equipped with asynchronous traction motors, which provide high operational reliability and improved energy efficiency.

Analyses conducted at locomotive depots and **JSC "O‘ztemiryo‘lmashta'mir"** indicate that a significant proportion of traction motor failures is associated with their thermal condition [1,6]. In particular, during heavy-haul operation and movement through mountainous regions, elevated temperatures are observed in the stator windings, rotor, and bearings. Such thermal stresses accelerate insulation degradation and reduce the overall efficiency and operational lifetime of the traction motors.

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Consequently, continuous monitoring and analysis of the thermal condition of traction motors play a crucial role in improving the operational reliability of electric locomotives.

This study investigates the thermal and humidity conditions of traction motors using the **3ES5K "Ermak"** mainline electric locomotive as a representative case study.

Statistical analyses indicate that traction motors account for the largest proportion of failures occurring in mainline electric locomotives. According to available operational statistics, failures associated with traction motors constitute approximately **25–30%** of all locomotive failures. This high failure rate is primarily attributed to severe operating conditions, increased traction loads, and elevated thermal stresses experienced during operation. Therefore, continuous assessment of the technical and thermal condition of traction motors is essential for enhancing locomotive reliability, operational safety, and maintenance efficiency.

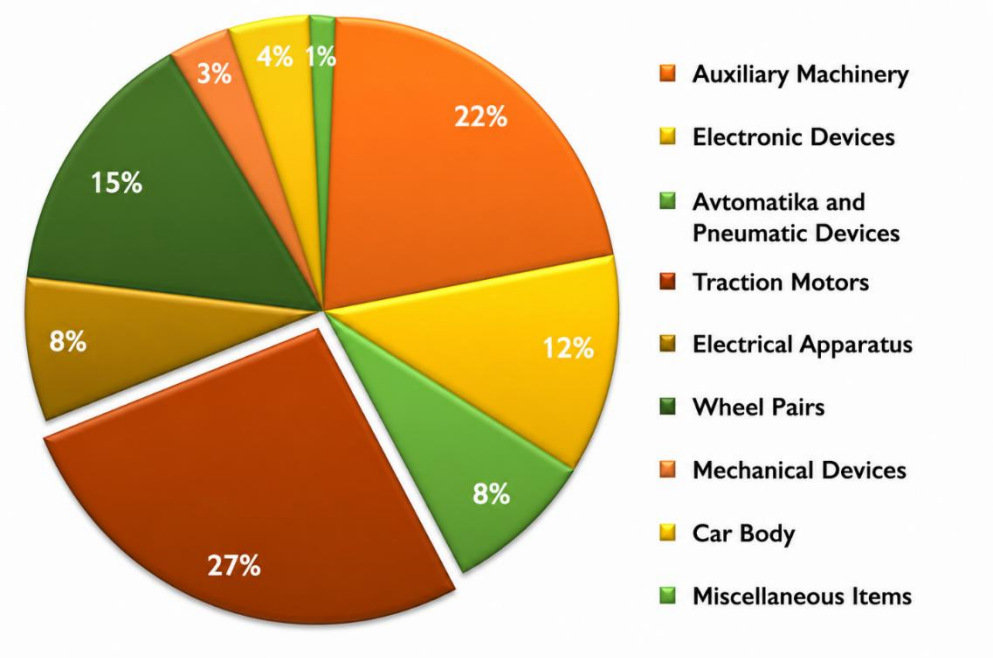


Figure 1. Distribution of Equipment Failure Rates in ERMAK Series Electric Locomotives

Abbreviations: ITSC – *Inter-turn Short Circuit*; **MAB** – *Motor-Axle Bearing*; **CW** – *Compensating Winding*; **IP** – *Interpole*; **MP** – *Main Pole*.

Influence of Ambient Air Conditions on Traction Motors

One of the most significant factors adversely affecting the insulation system of traction electric motors is the combined influence of **humidity** and **temperature**. When moisture penetrates the insulation material, both its volume and surface resistivity decrease, dielectric losses increase, and the electric field distribution becomes non-uniform [1]. As a result, the dielectric strength of the insulation deteriorates, increasing the probability of short circuits and insulation breakdowns.

The accumulation of moisture in traction motors is most often associated with insufficient efficiency of the ventilation system. The distribution of failures occurring in the components of traction electric motors used in electric locomotives is presented in **Table 1**.

Table 1. Distribution of Failures in Traction Electric Motor Components (%)

Type of Failure	**2024**	**2025**
Breakdown of insulation and high-voltage circuit	39	54
Failure of interpole windings and inter-turn short circuit	14	14

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Type of Failure	2024	2025
Failure of the main pole windings and inter-turn short circuit	12	19
Damage to the connections between the main pole, interpole, and compensating winding	11	15
Lubricating oil leakage onto the frame	10	16
Collector commutator wear	9	11
Damage to the terminals of the main pole, interpole, and compensating winding	4	6
Weakening of the interpole fastening	4	6
Melting of commutator segments	3	10
Damage to traction motor output cables	3	6
Breakdown and inter-turn short circuit in the compensating winding	1	3

Furthermore, under low-temperature operating conditions, moisture condensation may occur on the internal components of the traction motor. As a result of condensation, the insulation absorbs moisture, particularly through the exposed ends of the windings. This phenomenon deteriorates the electrical insulation properties, reduces its dielectric strength, and consequently decreases the operational reliability of the traction motor (**Figure 2**).

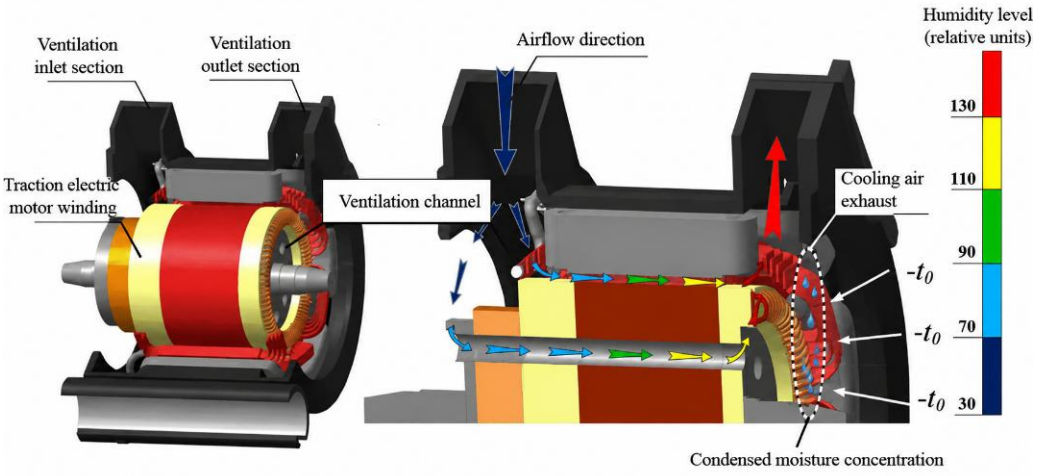
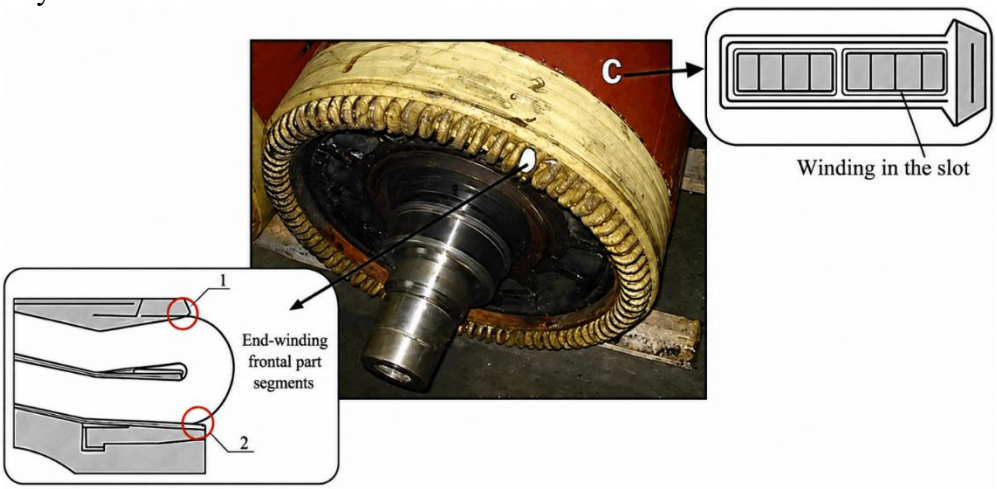


Figure 2. Formation of Condensed Moisture During Ventilation of the Traction Electric Motor in the 3ES5K “Ermak” Electric Locomotive

When a traction electric motor operates under low-temperature conditions, moisture condensation may occur on certain internal components. Under the influence of a cold ambient environment, moisture begins to accumulate in the rear section of the motor. Consequently, when the motor is switched off, excessive moisture accumulates in the frontal section, increasing the likelihood of water penetrating into the stator slots containing the winding conductors. The formation of condensed moisture is also observed when electric locomotives are parked in heated depots while their traction motors remain unheated during cold seasons, or during operation through long artificial structures such as tunnels [1]. Under these conditions, temperature gradients between the surrounding air and the motor components significantly increase the possibility of moisture accumulation inside the motor. Structural analysis indicates that moisture primarily penetrates the insulation system through the exposed end windings. The active part of the windings is located inside the stator slots and is

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protected by textolite slot wedges, providing relatively effective insulation against moisture ingress. However, the end-winding conductors are not protected to the same extent and are therefore considerably more susceptible to moisture exposure. As a result, insulation degradation in these regions occurs more rapidly, increasing the risk of electrical failures and reducing the operational reliability of the traction motor.



1 – Upper end-winding frontal part segment
2 – Lower end-winding frontal part segment
C – Stator frame (housing)

Figure 3. Moisture Penetration Paths into the Stator Winding Slots Caused by Design Imperfections of the Traction Motor Armature Windings in an Electric Locomotive (1, 2 – Potential Moisture Ingress Zones)

It is through these locations that moisture penetrates into the winding insulation, resulting in partial electrical discharges and subsequent insulation degradation. According to the statistical analysis reported by **S.A. Babichev**, failures of the stator end-winding region account for approximately **36%** of all failures in electrical machines [1]. Furthermore, the electric field intensity increases at the point where the stator core exits into the end-winding region, making this area particularly susceptible to insulation deterioration.

Figure 3 illustrates the potential paths of moisture ingress resulting from design imperfections in the stator winding structure of asynchronous auxiliary electrical machines used in traction rolling stock. The regions marked **1** and **2** indicate the zones where moisture is most likely to penetrate into the end-winding insulation. These areas are also characterized by elevated electric field intensity on the surface of the winding insulation. Consequently, surface electrical discharges may develop along the insulation surface. As the applied voltage increases, these discharges can propagate over progressively longer distances until they spread across the entire end-winding insulation surface.

The inception voltage of both discharge stages (kV) can be described by the generalized **Toepler equation**.

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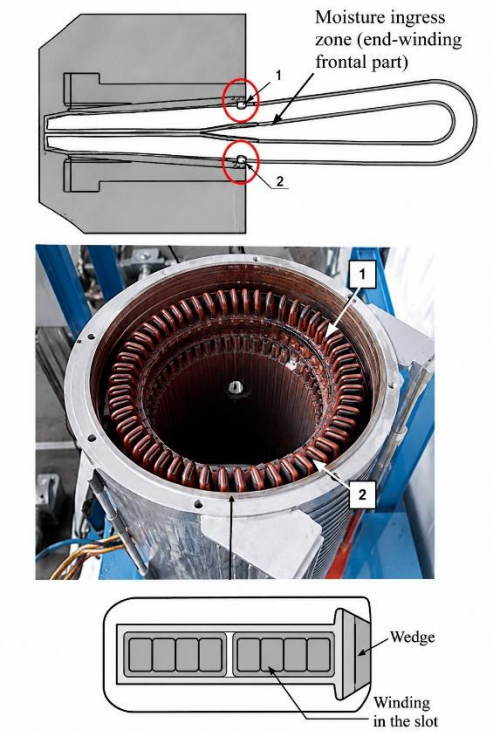
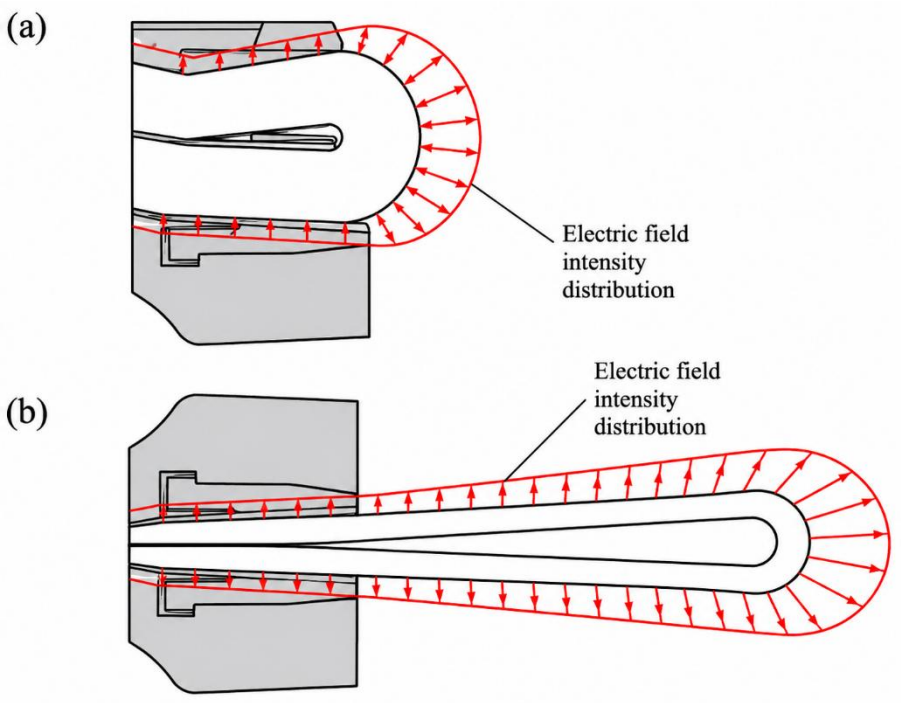


Figure 4. Potential Moisture Ingress Locations The distribution of the electric field intensity in the **end-winding region of the traction motor armature** of an electric locomotive **(a)** and in the **stator of the asynchronous traction motor (b)** is presented in **Figure 5**.



Surface electrical discharges can be mitigated by modifying the insulation design of the end-winding region through the application of a high-resistance semiconductive coating to its surface. In

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addition, the winding insulation may suffer significant damage due to vibration loads acting on the traction electric motor (TEM) during operation. The vibration of the traction electric motor is caused by both mechanical and electromagnetic forces. These forces can be classified according to their operating conditions as those occurring during load variations, transient and emergency operating conditions, and steady-state operation. They can also be categorized according to the components they affect, including the stator core, the end-winding assembly, and individual conductors or coils located within the stator slots. The most severe vibration effects occur at the locations where the conductors or coils emerge from the stator slots into the end-winding region. Vibrations in these areas accelerate insulation deterioration and promote premature insulation aging. Depending on the supply frequency, the end-winding region may vibrate within two principal frequency ranges. The first corresponds to the fundamental power-supply frequency, which is mainly generated by mechanical excitation, while the second corresponds to twice the supply frequency, produced by electromagnetic forces acting on the current-carrying phase conductors. Mechanical vibrations are primarily caused by the rotation of the traction motor rotor. These vibrations may result from rotor imbalance, shaft misalignment, bearing defects, or electrical faults within the rotor, such as short-circuited windings or, in the case of squirrel-cage induction motors, broken rotor bars. Electromagnetic vibrations arise from the electromagnetic forces acting between the stator windings as electric current flows through them. Under normal operating conditions, these forces are relatively small and are effectively absorbed by the supporting structure of the end windings. However, during severe electrical disturbances, such as short-circuit faults, the current may increase to approximately ten times its rated value. Since the electromagnetic force is proportional to the square of the current, the forces acting on the end-winding structure may become up to one hundred times greater than those experienced under normal operating conditions. Such excessive forces can cause mechanical deformation of the windings, insulation damage, and ultimately lead to failure of the traction electric motor.

Thermal Conditions of Asynchronous Traction Motors and Failures Caused by Overheating

Asynchronous traction motors are the primary energy conversion units of electric locomotives, and their operational reliability is directly dependent on their thermal condition. During the conversion of electrical energy into mechanical energy, various losses occur within the motor, resulting in heat generation.

The principal factors contributing to motor overheating include the following:

High-load operation. During heavy-haul transportation and operation on steep gradients, the motor current increases significantly, leading to greater heat generation in the stator and rotor windings due to increased copper losses [2,3].

Low-speed, high-torque operation. Under these operating conditions, rotor slip increases, resulting in higher copper losses and a rapid rise in motor temperature. Copper losses represent the thermal energy dissipated in the stator and rotor windings as a result of electric current flowing through their conductors.

The principal failures associated with excessive heating of the traction motor are summarized in **Table 2**.

Table 2. Major Failures Caused by Overheating in Traction Motors

Failure Type	Cause	Consequence
Insulation degradation	Temperature > 140 °C	Short circuit
Increase in winding resistance	Overheating	Reduction in efficiency
Bearing failure	Lubricant overheating	Increased vibration

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Failure Type	Cause	Consequence
Rotor deformation	Thermal expansion	Increased noise
Complete motor failure	Excessive overheating	Catastrophic failure

In asynchronous traction motors, heat is generated primarily as a result of **electrical** and **mechanical losses**. Thermal energy tends to accumulate in specific motor components, making these regions the most susceptible to degradation and failure. Consequently, continuous monitoring and assessment of the thermal condition of these critical components are essential for ensuring the reliability, safety, and service life of traction motors.

Stator windings (the most thermally stressed component

Rotor (particularly under low-speed operating conditions)

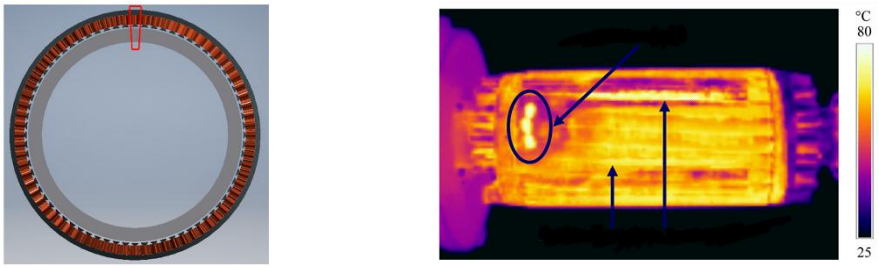
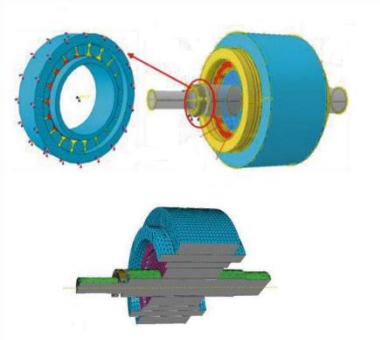


Figure 6. Failure Susceptibility of Motor Components Due to Overheating

The thermal condition of a traction electric motor is primarily determined by the heat generated in the stator windings, rotor, and bearings. An increase in load, prolonged operation at low speeds, and reduced efficiency of the cooling system lead to a rise in the motor temperature. The thermal condition can be predicted based on operating parameters such as current, rotational speed, and temperature, enabling the early detection of motor overheating. Such predictive monitoring facilitates the prevention of failures, improves the operational reliability of the traction motor, and extends its service life.

Bearings – the primary source of mechanical heating.

Insulation material degradation





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Figure 7. Locations of Overheating in Bearings and Insulation Materials

Main Approaches to Predicting the Thermal Condition

The thermal condition of a traction electric motor can be predicted using several fundamental approaches. The first approach is mathematical modeling, in which the amount of heat generated in the motor is calculated based on electrical current, load conditions, and cooling performance. The second approach is sensor-based monitoring, where the temperature of the stator, rotor, and bearings is continuously monitored in real time using temperature sensors installed at critical locations. The third approach is artificial intelligence (AI)-based prediction, in which historical operating data are analyzed to forecast future temperature variations. The integrated application of these methods enables the prevention of motor overheating and ensures reliable operation.

Key Parameters for Thermal Condition Prediction

To accurately predict the thermal condition of an asynchronous traction motor, several important operational and technical parameters should be continuously monitored. These parameters are directly related to the motor load and cooling conditions and make it possible to identify temperature rise trends before overheating occurs.

The principal monitoring parameters include: Traction current

– an increase in current results in higher copper losses and increased heating of the stator windings; Motor rotational speed – operation at low speed increases rotor slip, thereby intensifying heat generation; Stator winding temperature

– the primary indicator used to assess the condition of the insulation system; Bearing temperature – provides information about mechanical friction and the condition of the lubrication system; Ambient temperature and cooling system performance

– in mountainous regions, reduced air density decreases cooling efficiency and negatively affects heat dissipation.

Comprehensive analysis of these parameters enables real-time assessment of the motor's thermal condition and early prediction of potentially hazardous overheating conditions.

Research

Results During the course of this study, the thermal and moisture conditions of asynchronous traction motors used in mainline electric locomotives were analyzed under actual operating conditions. The results indicate that motor temperature is primarily influenced by traction current, rotational speed, cooling system efficiency, and ambient environmental conditions.

These findings are consistent with previously published studies [2,3]. The analysis further revealed that approximately 25–30% of all failures occurring in mainline electric locomotives are associated with traction electric motors. In particular, heavy-haul operation in mountainous regions, prolonged low-speed operation, and reduced cooling efficiency significantly increase the thermal loading of the stator windings, rotor, and bearings. Consequently, insulation degradation, premature bearing failures, and reduced motor efficiency are frequently observed.

Under low-temperature conditions, moisture condensation forms inside the motor and penetrates the insulation through the end-winding region. This leads to non-uniform electric field distribution, the occurrence of partial discharges, and a reduction in the dielectric strength of the insulation system. Furthermore, both mechanical and electromagnetic vibrations, particularly in the region where the windings emerge from the stator slots, accelerate insulation aging and degradation. The analysis of published studies and experimental observations indicates that when the traction current exceeds its rated value by approximately 20%, the temperature of the stator windings increases sharply. Likewise, under low-speed operating conditions, increased rotor slip results in greater thermal losses. A

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reduction of 15–20% in cooling system efficiency causes a rapid increase in motor temperature. Therefore, the combined application of sensor-based monitoring, mathematical modeling, and artificial intelligence-based thermal prediction is recommended for reliable thermal condition assessment. The scientific novelty of this study lies in the proposed approach for evaluating the thermal condition of asynchronous traction motors operating in mountainous regions. The proposed methodology is based on the integrated analysis of electrical current, rotational speed, temperature, and moisture, providing a comprehensive framework for assessing the thermal state of traction motors under real operating conditions.

Conclusion

The conducted research demonstrates that assessing and predicting the thermal condition of traction electric motors is an important scientific and engineering task for improving the operational reliability of mainline electric locomotives. The results indicate that motor temperature is mainly influenced by high loading conditions, prolonged low-speed operation, and reduced cooling system efficiency. In addition, moisture condensation under low-temperature conditions adversely affects the electrical properties of insulation materials. Consequently, partial electrical discharges may occur, leading to insulation degradation and eventual motor failure. Based on the obtained results, the following measures are recommended to improve the reliability of traction electric motors: continuous monitoring of the motor thermal condition; improvement of cooling system efficiency; reduction of moisture ingress into the motor; application of mathematical modeling and artificial intelligence techniques for temperature prediction. The implementation of these approaches will contribute to extending the service life of asynchronous traction motors while improving the operational reliability and safety of electric locomotives.

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